Modelling of transport of radioactive substances from the Siberian Chemical Combine by the Tom and Ob rivers*

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Abstract. Observations carried out in the frame of the ISTC project 3547 [1] were used to parameterize and validate the model of radionuclides transport from Siberian Chemical Combine (SCC) by the Tom and Ob rivers and also to assess discharges of radioactive substances from SCC to the Tom River and to estimate possible contamination of the rivers in case of accidents.

1. INTRODUCTION

The SCC was founded about 60 years ago and is the biggest Nuclear Fuel Cycle plant in Russia. The main sources of radioactive contamination of the Tom River were its industrial reactors. The last of the reactors was closed in 2008. Contaminated water discharges from SCC were carried out through the Romashka River to the Chernilschikovskaya channel – the right distributary of the Tom River [2-8]. Observations of specific activities of radioactive substances in the Tom and Ob rivers were used to assess discharges of radioactive substances from the SCC. The assessment was carried out with the use of the model based on the two-dimensional equation of advection and dispersion. It takes into account exchange of radionuclides between water column (solute, suspended particles) and bottom sediments [9].

In current work the following additional assumptions were made:

- Influence of longitudinal dispersion is negligible in comparison with advection. Only lateral dispersion is taken into account;
- Characteristics of a river channel are constant (see. Table 3).

The system of differential equations describing migration of radionuclides is as follows:

$$\begin{cases} \dfrac{\partial C_w}{\partial t} = E_y \dfrac{\partial^2 C_w}{\partial y^2} - u\dfrac{\partial C_w}{\partial x} - \lambda C_w - \dfrac{C_w \nu \alpha_{Tw}}{H} + \dfrac{C_b \psi \alpha_{Tb}}{H} + \dfrac{\beta}{H} * (\alpha_{Pb} C_b - \alpha_{Pw} C_w) + F; \\ \dfrac{\partial C_b}{\partial t} = - \lambda C_b + \dfrac{C_w \nu \alpha_{Tw}}{h} - \dfrac{\psi C_b \alpha_{Tb}}{h} - \dfrac{\beta}{h}(\alpha_{Pb} C_b - \alpha_{Pw} C_w) - \dfrac{\gamma \alpha_{Pb} C_b}{h}. \end{cases} \qquad (1)$$

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Where: 't' is time, s; 'F' describes sources of a radionuclide, Bq/(m^3*s); 'y' is a distance from the right bank, m; 'x' is a distance downstream from the source of contamination, m; 'C_w' and 'C_b' are the activities of a radionuclide per unit volume of water and bottom sediments respectively, Bq/m^3; 'λ' is the radioactive decay constant, s^{-1}; 'H' is the average depth of a water object, m; 'u' is the flow velocity, m/s; 'h' is the thickness of the upper (effective) layer of bottom sediments, m; 'β' is the coefficient of diffusive mass exchange of a radionuclide between water column and upper layer of bottom sediments, m/s; 'γ' is the coefficient of diffusive mass exchange of a radionuclide between upper and lower layers of bottom sediments, m/s; 'υ' is the effective sedimentation rate of suspended particles, m/s; ψ is the intensity of resuspension, m/s; 'α_{pw}' and 'α_{pb}' are fractions of a radionuclide dissolved in water column and in upper layer of bottom sediments respectively, dimensionless; 'α_{Tw}' and 'α_{Tb}' are fractions of a radionuclide sorbed on particles in water column and in upper layer of bottom sediments respectively, dimensionless; E_y - the coefficient of lateral turbulent dispersion, m^2/s.

Values of α_{Tw}, α_{Tb}, α_{Pw}, α_{Pb} can be determined with the use of well-known dependencies:

$$\alpha_{Pw} = \frac{1}{1 + S_1 k_{dw}}, \quad \alpha_{Tw} = \frac{S_1 k_{dw}}{1 + S_1 k_{dw}}, \quad \alpha_{pb} = \frac{1}{1 + m k_{db}}, \quad \alpha_{Tb} = \frac{m k_{db}}{1 + m k_{db}} \qquad (2)$$

where 'k_{dw}' is the partitioning coefficient of a radionuclide between water and suspeneded matter, m^3/kg; 'k_{db}' – the partitioning coefficient of a radionuclide between poral water and solid phase, m^3/kg; 'S_1' – the concentration of suspended matter in water, kg/m^3; 'm' – the air-dry weight of unit volume of bottom sediments, kg/m^3.

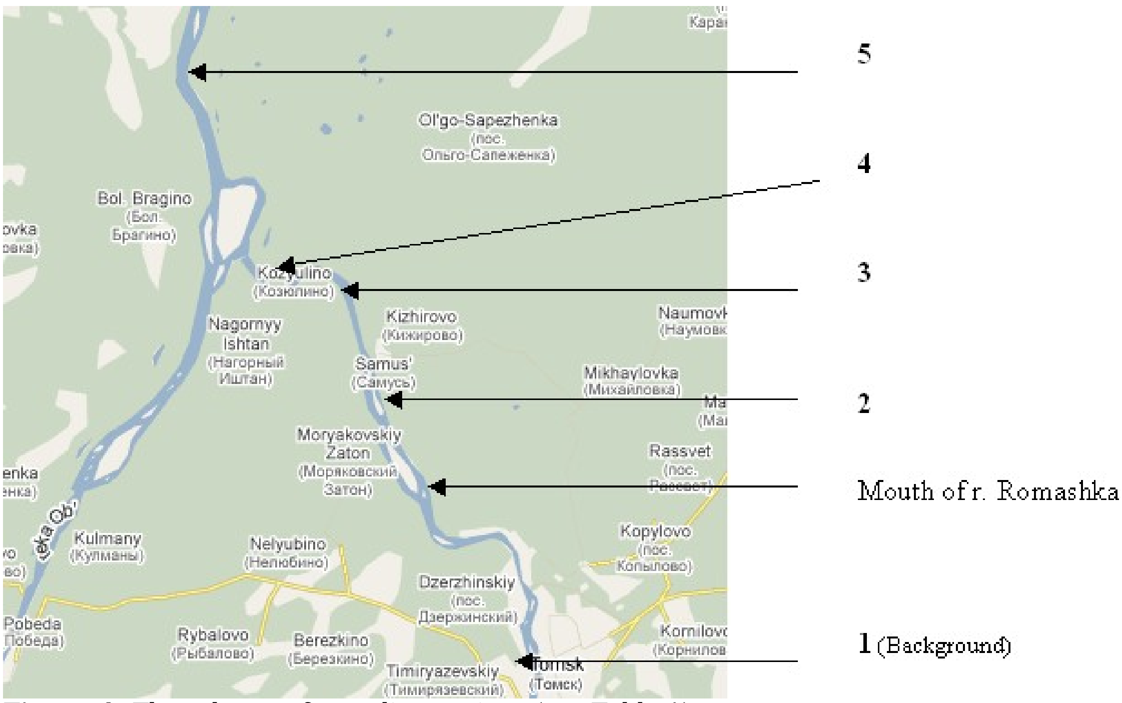

Figure 1. The scheme of sampling regions (see Table 1).

With the use of constants 'λ_1', 'λ_2', 'λ_{12}' and 'λ_{21}' (1) can be written as follows:

$$\begin{cases} \frac{\partial C_w}{\partial t} = E_y \frac{\partial^2 C_w}{\partial y^2} - u\frac{\partial C_w}{\partial x} - \lambda_1 C_w + \lambda_{12} C_b + F \\ \frac{\partial C_b}{\partial t} = \lambda_{21} C_w - \lambda_2 C_b \end{cases} \quad (3)$$

Values of the constants are determined from the following expressions:

$$\begin{cases} \lambda_1 = \lambda + \frac{\upsilon\alpha_{Tw} + \beta\alpha_{Pw}}{H} \\ \lambda_2 = \lambda + \frac{\psi\alpha_{Tb} + \beta\alpha_{Pb} + \gamma\alpha_{Pb}}{h} \\ \lambda_{12} = \frac{\beta\alpha_{Pb} + \psi\alpha_{Tb}}{H} \\ \lambda_{21} = \frac{\beta\alpha_{Pw} + \upsilon\alpha_{Tw}}{h} \end{cases} \quad (4)$$

Hydrological data about the Chernilschikovskaya channel are scarce. That's why the width of the channel was estimated on the base of satellite photos (www.google.com) while flow velocity on the base of expression:

$$u = C_{sh}\sqrt{RI}, \quad (5)$$

Where 'R' is the hydraulic radius, which is approximately equal to average depth, m; 'I' is slope of a river; 'C_{sh}' is the Shesi's coefficient, which describes resistance of the friction between water flow and bottom sediments. The coefficient can be estimated with the use of the Manning's expression.

The empirical Karaushev's expression was used to estimate 'E_y':

$$E_y = \frac{Hu(B/H)^{1,38}}{3524}, \quad (6)$$

Where 'B' is the width of a river, m.

2. ASSESSMENT OF RADIOACTIVE DISCHARGES TO THE TOM RIVER DURING OPERATION OF THE INDUSTRIAL REACTORS

Let us assume that discharges were steady and lasted for a long time. Let us also assume that the channel data and hydrological characteristics of the rivers were constant. Then time derivatives in (1) can be set to zero ($\frac{\partial C_w}{\partial t} = \frac{\partial C_b}{\partial t} = 0$). Thus, for a steady-state problem, solution of (1) is as follows:

$$C_w(x,y) = C_{background} + \frac{A}{Q}\left[1 + 2\sum_{n=1}^{\infty} exp\left(-\frac{n^2\pi^2 x E_y}{B^2 u}\right) cos\left(\frac{yn\pi}{B}\right)\right] exp\left(-\frac{kx}{u}\right) \quad (7)$$

$$C_b(x,y)=\frac{\lambda_{21}C_w(x,y)}{\lambda_2} \quad (8)$$

Here' $C_{background}$' - background activity of a radionuclide per unit volume of water, Bq/m^3; 'A' - intensity of inflow of a radionuclide to the Tom River, Bq/s; $k=(\lambda_1 - \frac{\lambda_{12}\lambda_{21}}{\lambda_2})$.

Assessment of radioactive substances inflow intensity to the Tom River was carried out on the base of observed activities of the radionuclides in the rivers, with the use of the expression (9), derived from (7):

$$A_i=\frac{Q\cdot C^i_w(x_i,y_i)}{\left[1+2\sum_{n=1}^{\infty}exp\left(-\frac{n^2\pi^2x_iE_y}{B^2u}\right)cos\left(\frac{y_in\pi}{B}\right)\right]exp\left(-\frac{kx_i}{u}\right)} \quad (9)$$

Here x_i, y_i are coordinates of an observation spot, m; 'C^i_w' is the observed activity, Bq/m^3. The observed activities [1] one can find in Table 1. The regions of sampling are shown on Figure 1.

Table 1. The observed activities that were used for the assessments.

Sampling spot		Date of sampling	^{137}Cs, Bq/m^3		^{90}Sr, Bq/m^3 filtrate	^{239,240}Pu mBq/m^3 filtrate	^{239}Np, Bq/m^3 suspended particles
			Suspended particles	filtrate			
Region 1 (r. Tom, background)		27.05.08	0.15±0.02	0.10±0.02	4.6±0.7		
		24.06.08	0.08±0.01		3.6±0.7		
		25.07.08			3,2±0,6		
		01.09.08	0.06±0.02		4,1±1,0	20±10	
		15.09.08			3,8±1,1		
		22.10.08			2,5±0,7		
Region 2 (r. Tom, 8 km downstream from the mouth of Romashka River)	r. b.	30.05.08	1.13±0.04	0.24±0.03	8.5±1.0	60±13	106±5
		26.06.08	0.47±0.03	0.54±0.08	11.1±1.3		
		01.08.08	0.34±0.03	0.15±0.08	12.1±1.5		
		31.08.08	0.74±0.04 2.4±0.1		8,3±2,1	45±11	
		29.09.08			7,1±1,8		
	m.	31.08.	0.30±0.				

		08	03				
Region 3 (r. Tom, 20 km downstream from the mouth of Romashka River)	r. b.	29.05.08	1.14±0.04	0.15±0.06	6.2±1.0	55±12	43±3
		27.06.08			8.7±1.1		
		29.07.08	0.61±0.04	0.78±0.07	10.5±1.4		
		29.08.08	0.70±0.06	0.67±0.09	6.2±1.0	41±9	
		24.09.08			5,7±1,5		
	l.b.	29.08.09	0.12±0.05				
Region 4 (r. Rom, 30 km downstream from the mouth of Romashka River)	r. b.	27-28.08.08	0.36±0.03			29±7	
	m.		0.44±0.05				
	l.b.		0.16±0.02				
Region 5 (r. Ob, 16 km downstream from the mouth of the Tom River)	r. b.	24-25.08.08	0.34±0.04			28±5	
	m.		0.18±0.02				
	l.b.		0.07±0.02				

* - r.b. – right bank, l.b. – left bank, m. – middle of a river.

Quantity of ^{239}Np in discharges of direct-flow reactors is always sufficient for reliable measurements. Data on actual discharges of this radioactive substance by SCC are available (see Table 2). That's why observed data on ^{239}Np were used for parameterization and validation of the model of the considered part of the Tom River.

Table 2. – Intensity of discharges of ^{239}Np to the Tom River, Bq/year [2-8].

Actual discharge							Permitted discharge
2002	2003	2004	2005	2006	2007	2008*	
$8.14\cdot10^{12}$	$6.23\cdot10^{12}$	$7.51\cdot10^{12}$	$13.0\cdot10^{12}$	$14.6\cdot10^{12}$	$12.6\cdot10^{12}$	$7.15\cdot10^{12}$	$1.48\cdot10^{13}$

* - operation of direct-flow reactors were terminated 5.07.2008

Assessment of the intensity of discharges carried out in accordance with (9) on the base of ^{239}Np observed activity in water - $(13.6\pm0.3)\cdot10^{12}$ is in satisfactory agreement with data in Table 2. It enables one to use estimated values of characteristics of the Chernilschikovskaya channel for assessment of other radionuclides inflow intensity. In Tables 3 and 4 one can find values of parameters used for the assessments. In Table 5 one can find intensity of discharges assessed on the base of observed activities.

Table 3. Channel data and hydrological characteristics used for modeling.

	Main channel of the Tom River	Chernilschikovskaya channel	Ob River
B, m	700.0	450	1000
H, m	4.0	4.0	6

h, m	0.1	0.1	0.1
Q, m^3/s	980	630	3000
E_y, m^2/s	0.49	0.27	0.99
S_1, kg/m^3	0.03	0.03	0.1
β , γ, m/s	$1.9 \cdot 10^{-8}$	$1.9 \cdot 10^{-8}$	$1.9 \cdot 10^{-8}$
υ , m/s	$1.0 \cdot 10^{-4}$	$1.0 \cdot 10^{-4}$	$1.0 \cdot 10^{-4}$
ψ , m/s	$2.7 \cdot 10^{-8}$	$2.7 \cdot 10^{-8}$	$9.1 \cdot 10^{-8}$
m, kg/m^3	1100	1100	1100

Table 4. Estimated values of partitioning coefficients of the radionuclides and their background activity.

	^{137}Cs	^{90}Sr	$^{239,240}Pu$	^{239}Np
k_{dw}	100	2	30	2.0
k_{db}	10	0.1	0.5	0.1
Background activity in water, Bq/m^3	0.1*	3.63**	0.02**	0

* - on suspended particles, ** - in filtrate

Table 5. Assessment of long-term discharges of the radionuclides to the Tom River, Bq/year.

^{137}Cs	^{90}Sr	$^{239,240}Pu$
$(2.2\pm1.7)\cdot10^{10}$	$(4.8\pm0.9)\cdot10^{10}$	$(6.5\pm1.9)\cdot10^{8}$

3. ESTIMATION OF POSSIBLE ACCIDENTAL CONTAMINATION OF THE TOM RIVER

A scenario of hypothetical accident was studied in the frame of ISTC project 3547. The scenario includes an accident followed by transport of radionuclides in the atmosphere and radioactive fall-out on the surface and the catchment area of the Tom River. A similar accident took place there on 06.04.1993 [10]. The most adverse fall-out conditions were assumed for assessment of the river contamination by long-living ^{90}Sr and ^{137}Cs. As no detailed information about possible source of contamination was available, the modeling estimations were done for “unit” amount of radioactivity (1 TBq of each of the radionuclides).

Modelling was carried out with the use of computer model Cassandra [11]. It enables computations in accordance with (1). A reach part of the Tom River with silty bed sediments and pronounced sedimentation, located 26-28 km downstream from the confluence with the Romashka River was taken into account. The reach reduces peak of specific activities of radionuclides (especially of ^{137}Cs) in the zone of contaminated water, moving downstream the river system. The reason is sedimentation of suspended particles, containing substantial fraction of ^{137}Cs, while the contaminated water is passing the reach. On the other hand afterward the silty bed sediments will become the source of secondary contamination of the water.

On the Figure 2 one can see distribution of the radionuclides activity along the Tom River in 10 and 20 hours after the fall-out. The fall-out on the river surface was assumed to be instantaneous and to affect area of 2 km along

the channel. Modelling results showed that after passing the reach mentioned above, peak activities of ^{137}Cs reduced from 93 to 19 kBq/m^3 and ^{90}Sr from 160 to 108 kBq/m^3. Maximum activity of ^{137}Cs (7 kBq/m^3) and ^{90}Sr (85 kBq/m^3) in the mouth of the Tom River is to be observed in 32 hours after the fall-out. In 40 days after the hypothetical accident, specific activity of ^{137}Cs in water of the reach part of the Tom River is to be 20-40 Bq/m^3. Specific activity of ^{90}Sr is to be 7-15 Bq/m^3 there. Maximum assessed specific activity of the radionuclides in the Ob River one can see in Table 6.

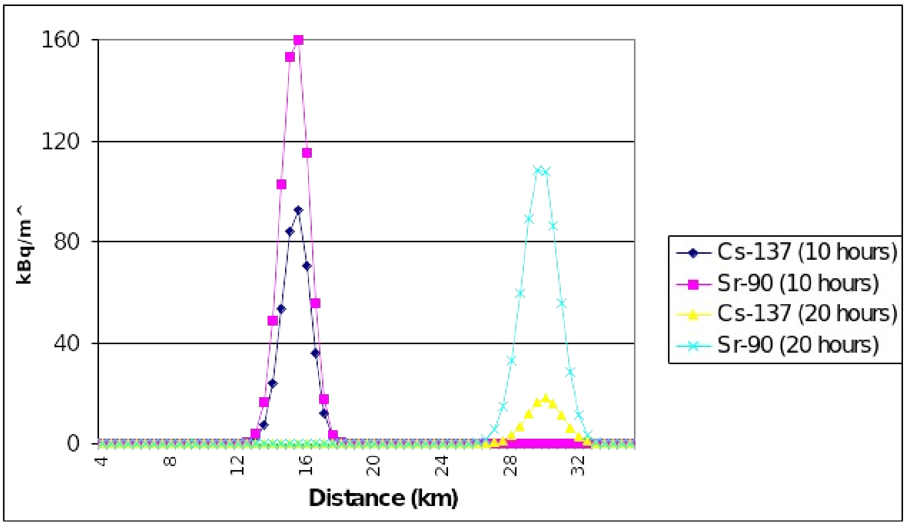

Figure 2. Distribution of radioactivity along the Tom River in 10 and 20 hours after the hypothetical fallout.

Table 6. Maximum exceeding of background activity in the Ob River, Bq/m^3.

	Right bank		Left bank	
	^{137}Cs	^{90}Sr	^{137}Cs	^{90}Sr
16 km downstream from the mouth of the Tom River	5000	88000	0	0
66 km downstream from the mouth of the Tom River	250	12600	66	1.5
130 km downstream from the mouth of the Tom River	46	6200	370	3

4. CONCLUSION

The study enabled one to use observed data for assessments of long-living radionuclides discharges to the Tom River that took place during operation of the industrial reactors on the SCC. The hypothetical accident was studied. Its scenario included transport of ^{90}Sr and ^{137}Cs in the atmosphere and their fall-out on the surface of the Tom River near the SCC. Modelling was carried out with the use of the computer model Cassandra. It provided estimation of spatial and temporal distribution of the radionuclides in the Tom and Ob rivers in case of fall-out of 1 TBq of each of the radionuclides.

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